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# A PROGRESS REPORT

# ON THE NON-EXISTENCE OF PEAK AND MINIMUM BOILING HEAT FLUXES AT LOW GRAVITY

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a progress report

# ON THE NON-EXISTENCE OF PEAK AND MINIMUM BOILING HEAT FLUXES AT LOW GRAVITY

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CONTENTS

# I INTRODUCTION

This progress report describes a continuation of work on the peak pool boiling heat flux on horizontal cylinders, carried out last year by Sun and Lienhard [1]. Their results showed that $q_{max}$ and $q_{min}$ data can be represented with correlations and predictions that take the form

$$\frac{q_{max}}{q_{max_F}} \text{ or } \frac{q_{min}}{q_{min_F}} = f(R') \qquad (1)$$

as long as the pressure is not high and the heater surface is uncomplicated. The subscripts, F, denote Zuber's values for the hydrodynamic transition heat fluxes, and

$$R' = \frac{R}{\sqrt{\dfrac{\sigma}{g(\rho_f-\rho_g)}}} \qquad (2)$$

Equation (1) is successful as long as $R'>0.1$ (i.e. if R and g are not very small), but when R' is small, it fails to correlate the data as can be seen in Figure 1, taken from [1]. The implication of this failure is that the dimensionless variables employed are no longer appropriate in this range. Furthermore, photographs show that the mechanism of transition is different in character as R' becomes small. This was clearly visible in photographs taken by Sun [1] and it was also shown clearly in several photographs by Pitts and Leppert [2].

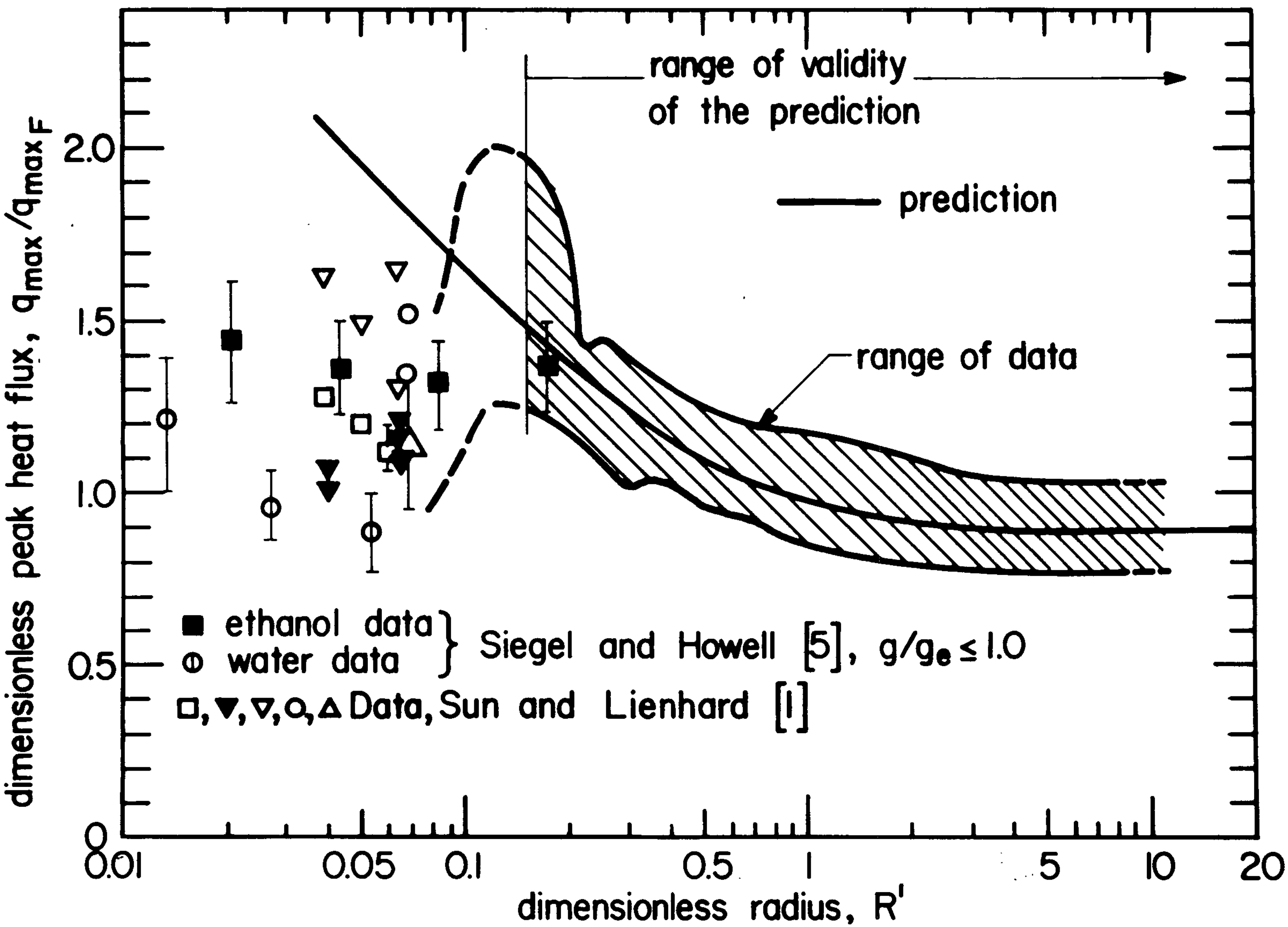


Fig. 1 General view of the results of the Sun-Lienhard prediction.

Several choices as to what variables should be omitted suggest themselves. The most obvious choice might be gravity, but this must be rejected. The zero-gravity case is singular since we doubt that any steady boiling mechanisms exist in it. We must also reject the temptation to throw out L since the heater must retain contact with the liquid within the nucleate boiling regime.

However the photographs suggest that the inertially dominated wave processes cease to exist at small R'. This is clearly visible in some of Siegel's movies [3] taken at the NASA Lewis Research Center. Siegel and his co-workers found that detachment of bubbles at low gravity is governed mainly by buoyancy and surface tension forces, with the inertial forces being very small. Thus another more realistic simplification might be the removal of inertia, as characterized by $\rho_f$, from the problem. If we restrict consideration to reduced pressures sufficiently low that $\sqrt{1+\rho_g/\rho_f} \simeq 1$, then the functional equation for $q_{max}$ or $q_{min}$ can be written in the following form

$$q_{max} \text{ or } q_{min} = f[\rho_g h_{fg},\ g(\rho_f-\rho_g),\ \sigma,\ L,\ \mu] \tag{3}$$

where we are tentatively ignoring the influence of surface chemical effects.

There are six variables in four dimensions, in equation (3). Thus we can characterize the problem with just two dimensionless groups as follows:

$$\gamma \equiv \frac{q_{max} \text{ or } q_{min}}{\rho_g h_{fg} \quad (\sigma /\mu)} = \gamma(L') \tag{4}$$

where $\gamma$ is the new dimensionless peak heat flux that would appear to be appropriate for $R'<<1$.

Data for wires with R' below .07 as given by Lienhard and Watanabe [4], Siegel and Howell [5], and Pitts and Leppert [2] are plotted on $\gamma$ versus R' coordinates in Figure 2. The results are only moderately gratifying. They indicate some correlation for small R' and increasing spread as R' increases beyond .03 to a range in which inertia becomes effective.

The fact that correlation is not particularly good, even at very small R', might well be attributed to possible variations in the surface chemistry among the various sets of data. It could also be because an R', even as low as 0.01, might still be above the asymptotic limit.

But before we accept either of these explanations we should recognize that there is a deeper implication to the evidence that inertia ceases to control the peak heat flux transition. If inertia is not important, then the whole concept of Zuber's hydrodynamic transitions ceases to have any revelance. Indeed we must then question whether or not any such transitions actually exist. Although $q_{max}$ data have been reported, so we know that some kind of identifiable change is present, these data are widely scattered.

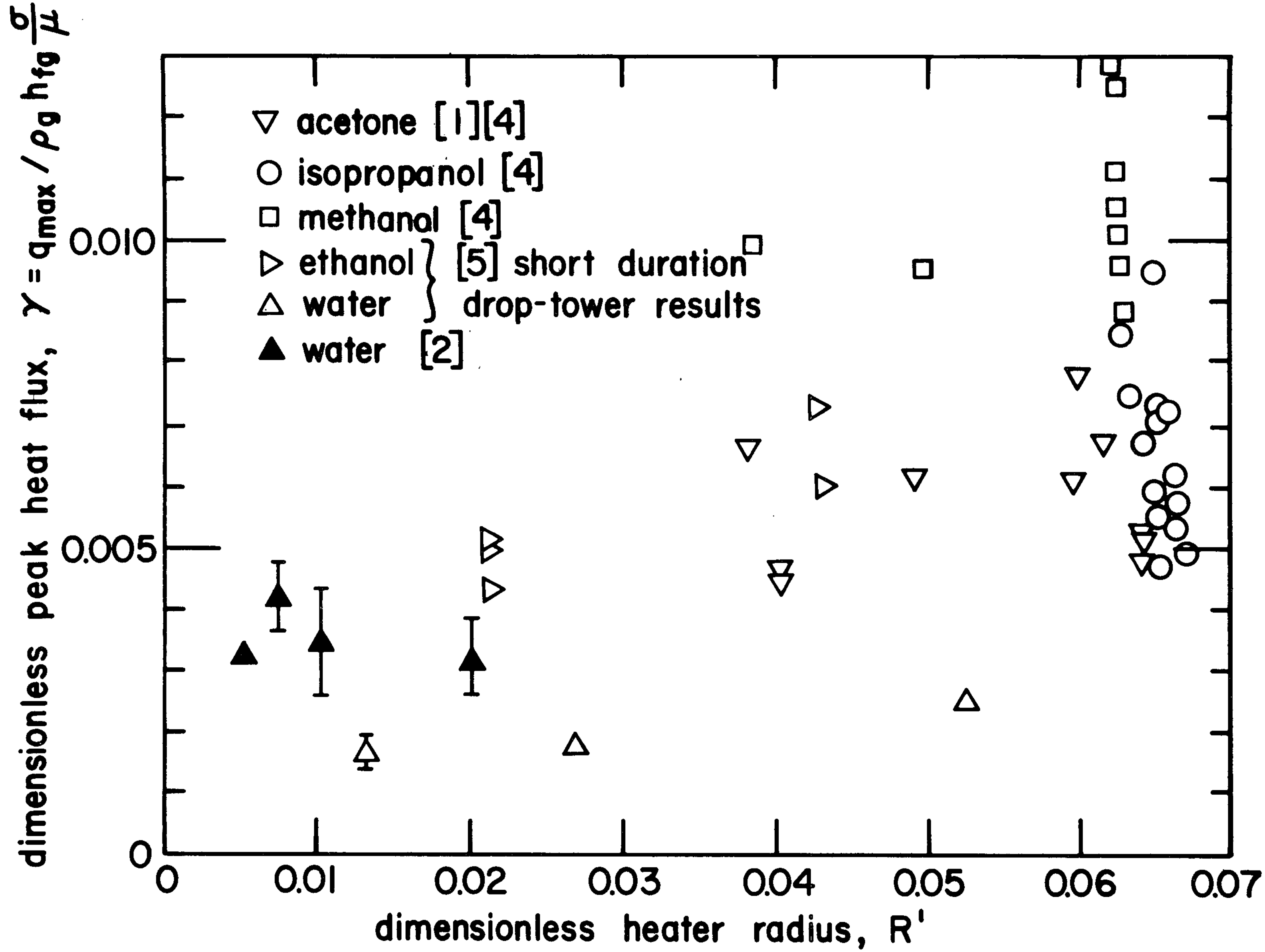


Fig. 2 Possible form of correlation for very small R'.

## II EXPERIMENT AND RESULTS

We therefore undertook to plot $q_{max}$ against wall superheat, $\Delta T$, experimentally to determine whether or not the peak and minimum transitions really occured when R' was small. To do this we set up experiments with 1 or 2 mil diameter wire in methanol. These wires were used as combination resistance heaters and resistance thermometers much as Nukiyama [6] did in 1934 or Van Stralen et al. [7] did in 1968 for larger wires with water.

The wire was mounted between two knife edges and immersed in a saturated pool of methanol. Current was supplied to the wire through two d.c. generators. The voltage across the wire was read directly on a digital volt-meter and the current through the wire was obtained by measuring the voltage across a standard 0.995 ohm resistor. The power supplied to the wire and the resistance of the wire were obtained from the voltage and current readings.

The wire was previously calibrated in a furnace and its resistance-temperature curve drawn using an accurate Wheatstone bridge (Universal Impedence Bridge, Electro-Measurements Incorporated). This calibration curve was then used to find the temperature of wire at various power inputs. Thus q vs $\Delta T$ curves were formed for the various wires. The probable errors in q and $\Delta T$, obtained in this way, were 2 1/2% and about 12°F. A typical q vs $\Delta T$ curve for a 1 mil platinum wire is shown in Figure 3. The reduced radius, R'

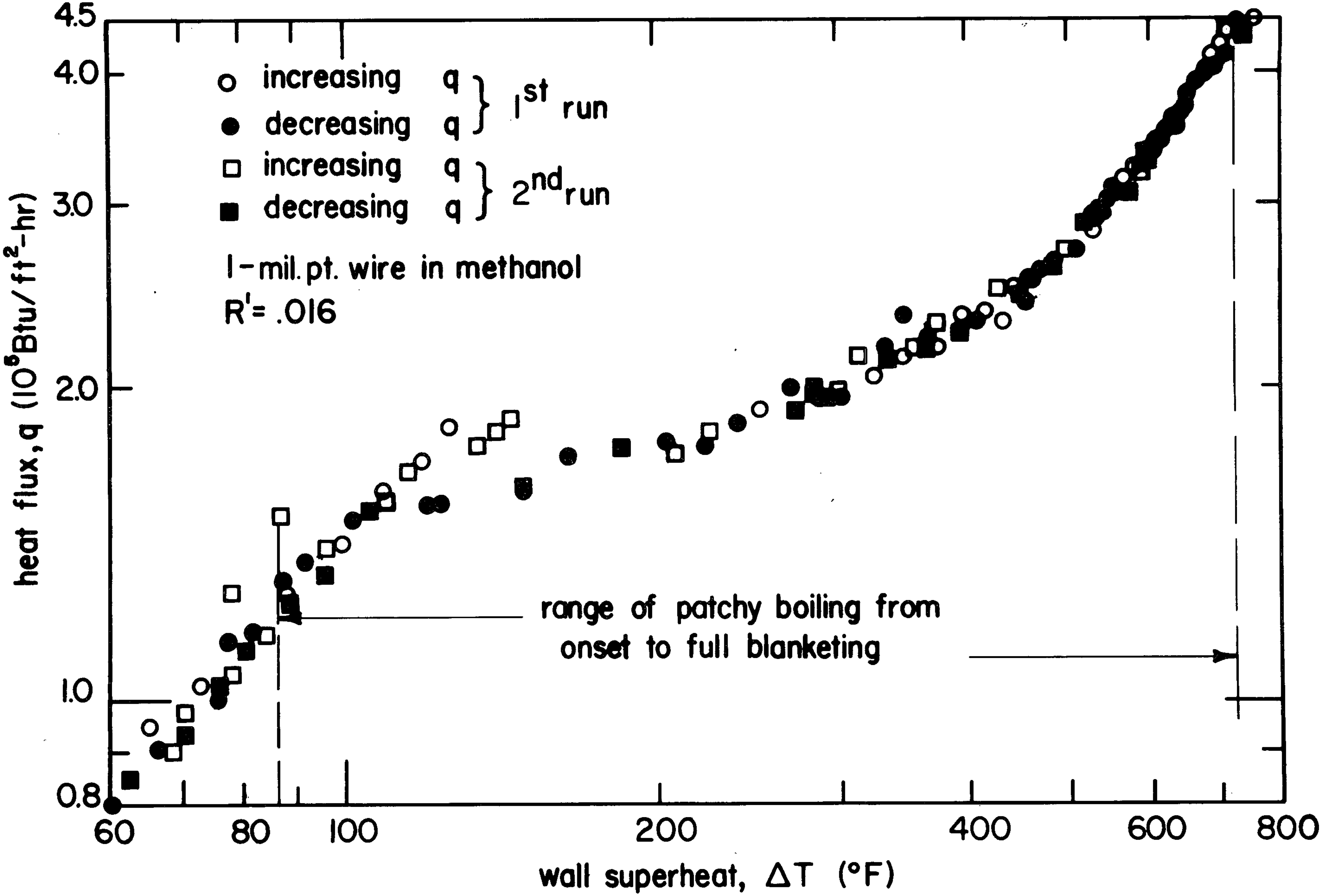


Fig. 3 Boiling curve for a small wire.

is .016 in this case.

Figure 3 shows that for low R', the peak and minimum heat fluxes vanish, hence the hydrodynamic transition which is obtained on larger wires does not appear to occur! However, the rate of increase of temperature with q becomes very rapid shortly after the first vapor appears on the wire. In all probability this is what has been reported as $q_{max}$ by prior investigators. This appears to explain why Sun and Lienhard were previously unable to correlate data for R'<0.1 on $q_{max}/q_{max_F}$ vs R' coordinates.

## III THE IDENTIFICATION OF A LOW R' BOILING MECHANISM

Physical Behavior of the Process. Careful scrutiny of motion and still pictures shows that for small R', the increase in heat flux produces not an increase of nucleation sites, as observed on larger wires, but vapor patches that somewhat resemble film boiling. These patches begin with the growth of a single bubble. This bubble spreads across a portion of the wire, persists a while, and then recedes. Then a similar patch starts at some other point, spreads over a small length of the wire and recedes again. The result is that we find vapor patches breaking out briefly all over the wire. The photos showed that the observed mode of boiling on the wire was like film boiling in the sense that the wire was blanketed with vapor and that there was apparently no liquid contact with the wire.

Elimination of an Erroneous Mechanism. The question then arises as to why the boiling process directly shifts to film boiling, bypassing the nucleate boiling regime. Apparently the original bubble being characteristically too small to buoy off, remains on the wire, insulating it. The wire temperature then rises sharply increasing the temperature in the adjacent unblanketed portion and triggering additional vaporization. The growing bubbles stay near the wire long enough to come in contact with each other. Mergers then occur between adjacent bubbles. The bubbles thus grow by successive mergers until they have enough buoyancy to overcome the surface tension forces that hold them to the wire. The wave action observed on larger wires could not be identified on these small wires even after these patches completely blanketed the wire.

To gain assurance that this was the correct mechanism of boiling we undertook the following analytical description of the patch growth. The time required to heat an insulated wire from the saturation temperature to the Leidenfrost point (on the order of 300°F for methanol) turned out to be extremely small -- on the order of a few microseconds for 1 mil platinum wire near the apparent "$q_{max}$" in saturated methanol. The time between vapor patches measured off the movies of the same wire under these conditions varied from as little as a fraction of a second to as much as 15.5 seconds. This means that heat conduction or convection from the wire is keeping it cool during the non-boiling phase.

We therefore considered the cooling of a circular cylinder of radius, R, with constant heat generation rate of $(2q/R)\,Btu/ft^3hr$. It was our first thought that the temperature of the liquid surrounding the wire keeps on rising until it reaches the Leidenfrost temperature. The liquid would then suddenly go into film boiling, taking with it a large amount of heat and lowering the temperature of the wire back almost to saturation. The process would then begin again, possibly at some other segment of the wire. Thus we sought to explain successive patches of film boiling appearing and disappearing.

We calculated the time required for the temperature of the liquid adjacent to the wire to rise from the saturation state to the Leidenfrost point, using a pure heat conduction model, and compared it with the time measured from movies. To do this we wrote the transient heat conduction equation for an infinite region bounded internally by a circular cylinder of radius R with constant heat flux q:

$$\frac{\alpha}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) - \frac{\partial T}{\partial t} = 0$$

The boundary conditions in this case are

$$-k\left.\frac{\partial T}{\partial r}\right|_{r=R} = q$$

$$T(r=\infty) = T_{sat}$$

$$T(t=0) = T_{sat}$$

The solution for $\alpha t/R^2 \gg 1$ is given by Carslaw and Jaeger [8] as

$$T - T_{sat} = \frac{qR}{2k}\,\ell n\left[\frac{4\alpha t}{CR^2}\right]$$

where $\ell nC = 0.57722$.

The above equation gave $t = 23.8$ seconds for $T - T_{sat} = 300°F$ and $q = 1.6 \times 10^5$ Btu/hr-ft$^2$. This exceeded the observed time between two successive patches at a point on the wire in all cases. The measurement, however, varied from a fraction of a second up to a maximum of 15.5 seconds. Since convection, if it removes a considerable amount of heat from the wire, will further slow down the process, we should expect the observed delay to exceed the prediction in all cases. Hence we had to discard the above conjecture.

A Viable Mechanism. In some of the movies it was observed that before film boiling starts or when film boiling ends, a single nucleation site remains. This site was similar to the single nucleation site observed on larger wires. Hence we opined that this nucleation site might trigger the propagation of the vapor patch. A single bubble on the wire might insulate it so that its temperature rises almost immediately up to some fairly high temperature. This hot spot in turn heats the adjacent unblanketed portion of the wire and its temperature also rises until it reaches a nucleation triggering level. This results in the axial propagation of the vapor patch.

Two typical close-up photographs are shown in Figure 4 to confirm that the wire is blanketed with vapor and that there is no liquid contact with the wire. Figure 5 shows the typical growth of a vapor patch as sketched from a high speed motion picture record.

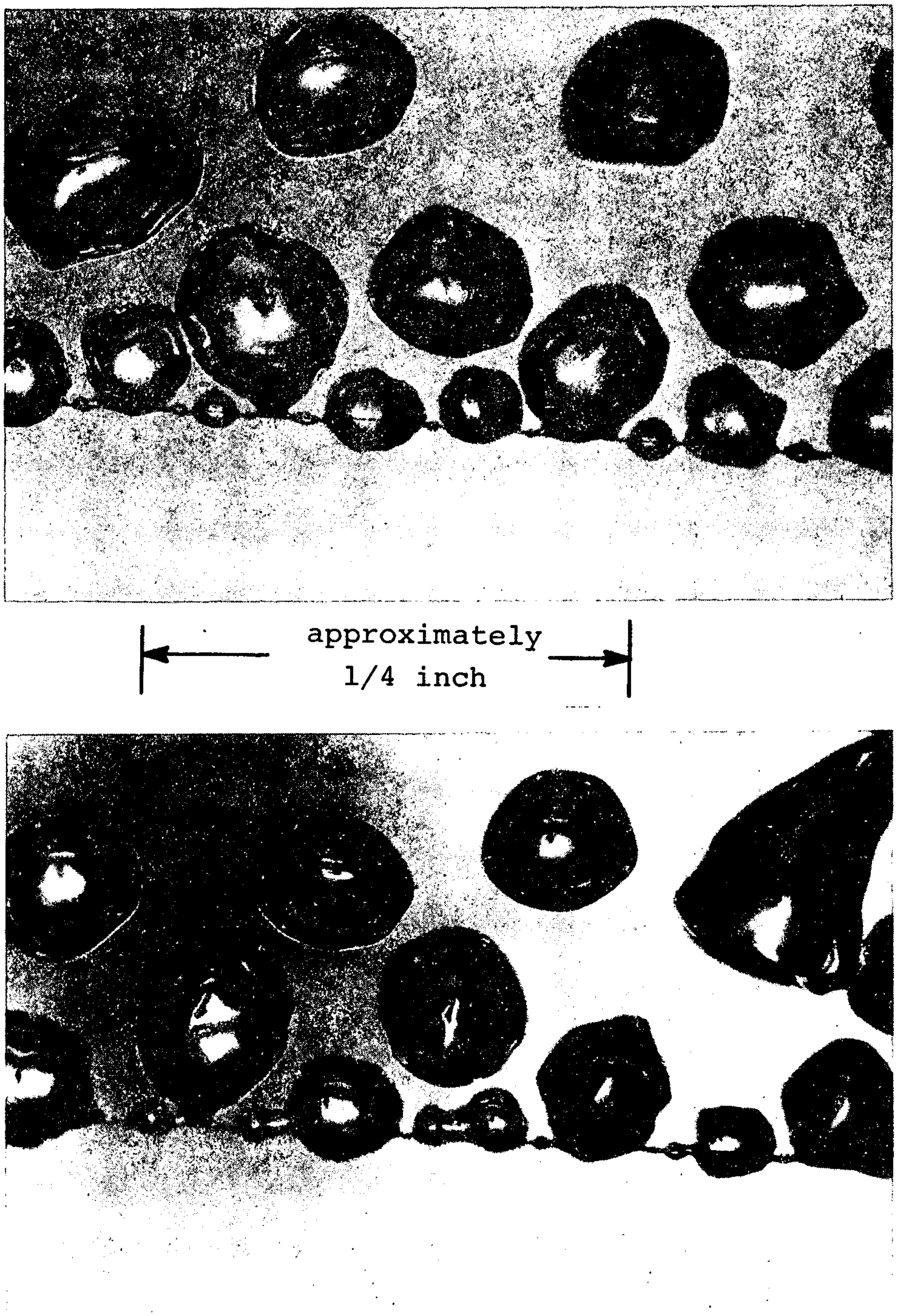


Fig. 4 Photographs of the bubble departure process within typical vapor patches. 1-mil platinum wire in saturated methanol. R'=0.016, 409,000 Btu/$ft^2$hr

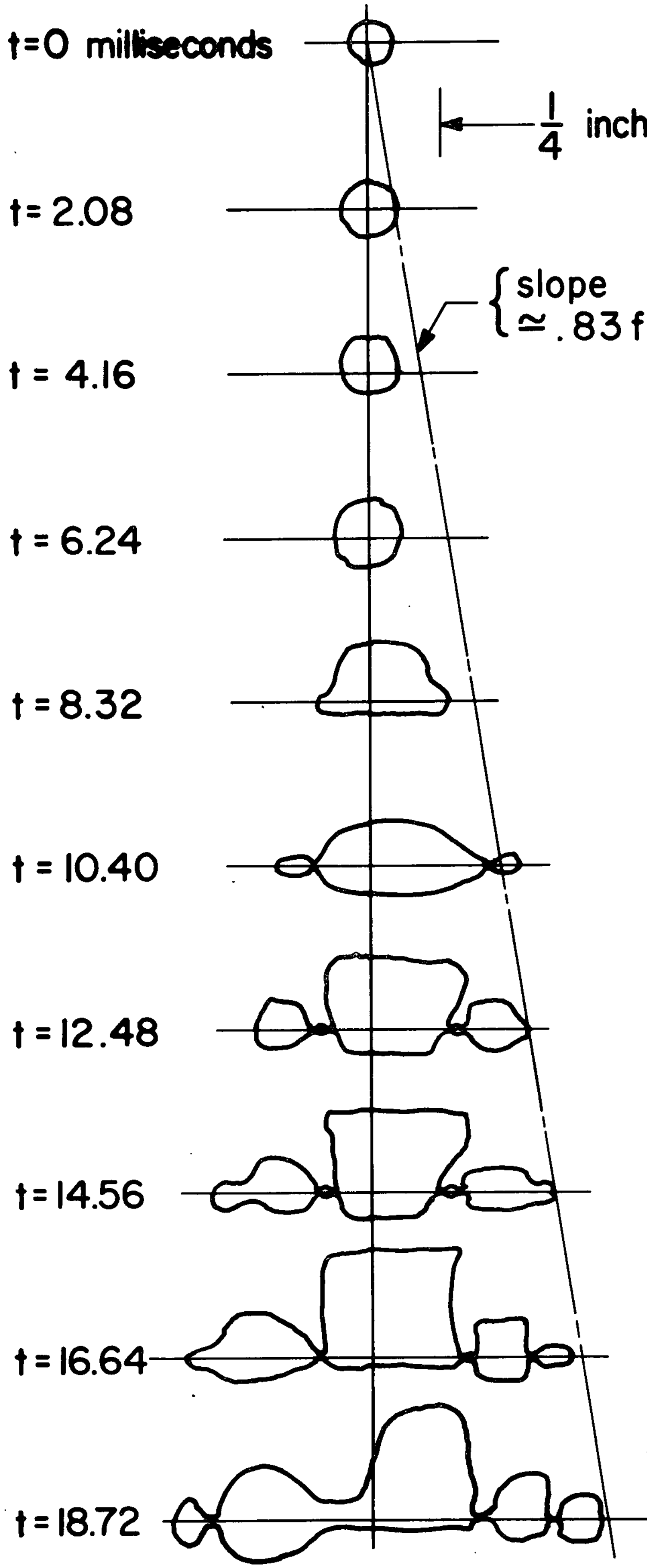


Fig. 5 A vapor patch propagation sequence illustrating propagation of a vapor front. 1 mil platinum wire. $R' = .016$, $q = 165{,}000$ Btu/ft$^2$hr.

The axial propagation of the patch apparently ceases when the blanketing bubbles finally achieve sufficient size to buoy off the wire, as a result of subsequent mergers. When this happens, some cooling is achieved within the blanket and the temperature at the vapor front can drop below the temperature that was required to trigger nucleation.

With further increases in the heat flux the wire becomes generally more and more covered with patches, but there is no other change in the boiling mode, as there would be on larger wires.

The mechanism described above is plausible as we compare it with the visual evidence available. However, to give it real credence we must show that its essential features are quantitatively predictable. Accordingly we shall next seek to predict the rate of propagation of the vapor front on the basis of this mechanism.

Rate of Propagation of the Vapor Front. We shall first solve the unidimensional heat conduction problems separately in both the blanketed and unblanketed portions of the wire. Then we shall couple the solutions together using the requirement that at the interface between the two regions, there is a common temperature.

We shall use the coordinate axes shown in Figure 6 in formulating the problems. In the unblanketed portion of the wire, the differential equation is

$$-\frac{u}{\alpha}\frac{d\theta}{dx} = \frac{d^2\theta}{dx^2} + \frac{G}{k} - \frac{hP\theta}{kA} \qquad (5)$$

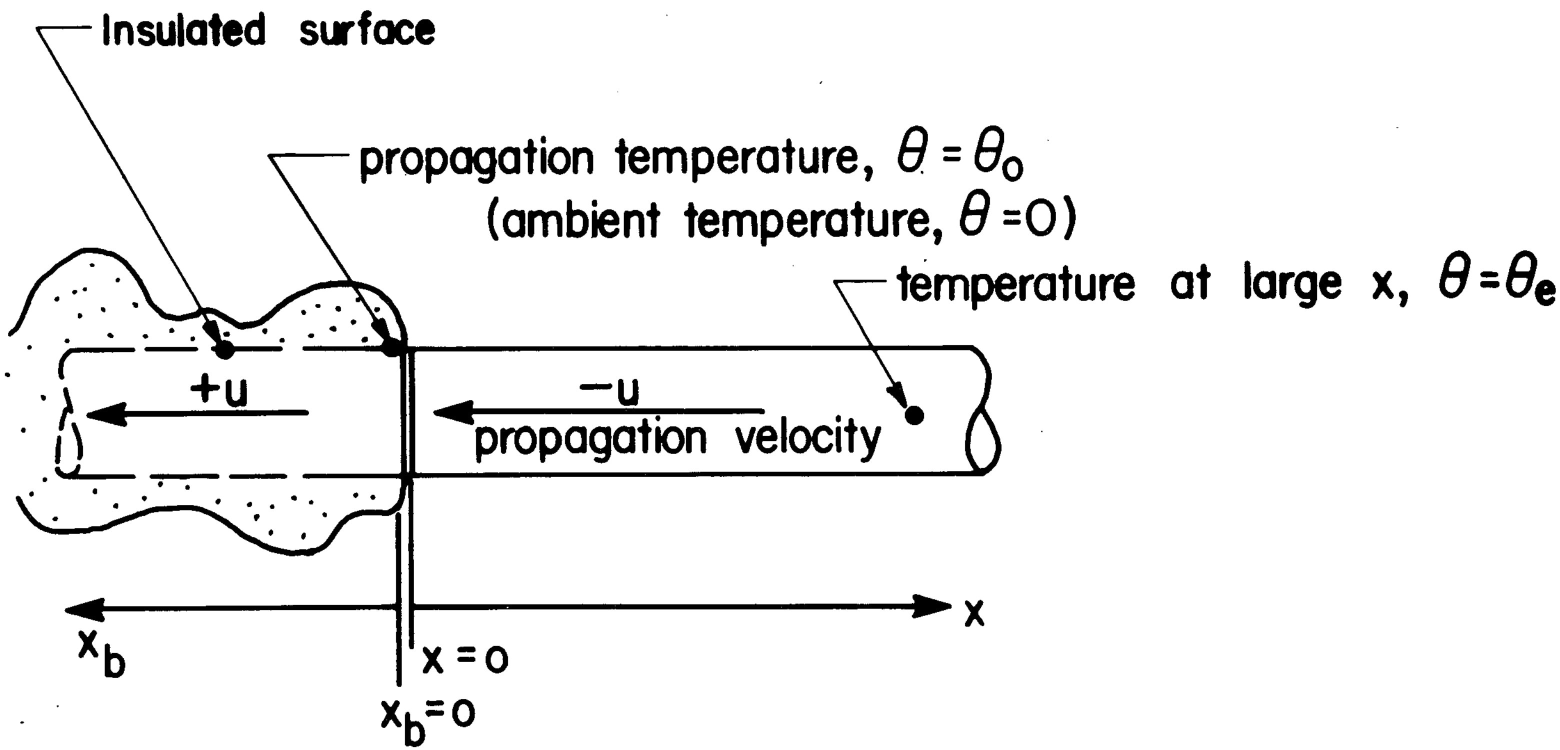


Fig. 6 Steady-state representation of advance of a vapor patch.

where $\theta$ is the temperature measured above the ambient saturation temperature. The boundary conditions are

$$\theta(x \to \infty) = \theta_e \quad \text{and} \quad -k \left.\frac{\partial \theta}{\partial x}\right|_{x=0} = \left\{\begin{matrix}\text{heat flux from} \\ \text{blanketed region}\end{matrix}\right\} \tag{6}$$

where $\theta_e$, the equilibrium temperature on a portion of the undisturbed wire, is equal to $q/h$.

To facilitate non-dimensionization of both this problem and that in the blanketed region let us consider the functional equation for u

$$u = u(\alpha,\ \theta_e,\ \theta_o,\ k,\ h,\ A/P) \tag{7}$$

There are seven variables in four dimenions. Thus, by the Buckingham Pi-Theorem, we should expect three dimensionless groups. For these we shall choose

$$\Theta_o \equiv \frac{\theta_o}{\theta_e}, \quad Pe \equiv \frac{u}{\alpha\sqrt{\frac{hP}{kA}}}, \quad \text{and } Bi \equiv \frac{h(A/P)}{k} \tag{8}$$

where $A/P = r/2$ for a cylinder.

The first dimensionless group shows relation between triggering temperature and equilibrium temperature. The second group is a kind of Peclet number involving the familiar fin constant, $\sqrt{hP/kA}$. It compares the propagation capacity of vapor front to the conduction capacity of wire. The Biot number, Bi, is typically on the order of $10^{-3}$ in the present problem, and should therefore exert no influence beyond assuring us that radial conduction can be ignored in the total problem. Thus equation (7) should reduce to

$$Pe = Pe(\Theta_o) \tag{9}$$

Returning to equations (5) and (6) with the following dimensionless groups suggested by equation (8):

$$\Theta \equiv \theta/\theta_e \quad \text{and} \quad \xi \equiv xN \quad \text{where} \quad N \equiv \sqrt{hP/kA} \tag{10}$$

we obtain

$$\Theta'' + Pe\Theta' - \Theta = -1, \qquad \Theta(\infty) = 1 \tag{11}$$

where we shall delay consideration of the second boundary condition. The solution of the system (11) is

$$\Theta - 1 = A \exp\left[-\left(\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{Pe^2}}\right) Pe\xi\right] \tag{12}$$

where A is as yet an undetermined constant.

For the blanketed portion of the wire, the governing differential equation is

$$\Theta'' - Pe\Theta' = -1 \tag{13}$$

where the independent variable is now $\xi_b = x_b N$. The boundary conditions on equation (13) are

$$\left.\frac{d\theta}{dx_b}\right|_{x_b \to \infty} = \frac{2q}{R} \frac{\alpha}{ku} \qquad \text{and} \qquad \theta(x_b=0) = \theta(x=0) \tag{14}$$

or

$$\frac{d\Theta}{d\xi_b} = \frac{1}{Pe} \qquad \text{and} \qquad \Theta(\xi_b=0) = \Theta_o \tag{14a}$$

The solution of this system is simply

$$\Theta = \Theta_o + \xi_b/Pe \tag{15}$$

Now if we combine equations (15) and (12) in the second of boundary conditions (6) we can obtain the following expression for A:

$$\frac{1}{Pe} = A\left(\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{Pe^2}}\right)Pe \qquad (16)$$

so equation (12) becomes

$$\Theta = 1 + \frac{\exp\left[-\left(\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{Pe^2}}\right)Pe\xi\right]}{Pe^2\left[\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{Pe^2}}\right]} \qquad (17)$$

Finally, the triggering temperature is obtained by setting $\xi = 0$ in this expression. Thus

$$\Theta_o = \frac{1/Pe^2 + \left[\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{Pe^2}}\right]}{\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{Pe^2}}}$$

Figure 7 shows equation (18) in graphical form.

The maximum typical vapor front velocity measured from motion pictures for the 1 mil platinum wire in saturated methanol was about 1.03 ft/sec. The value of the heat transfer coefficient, h, for natural convection calculated from McAdams' correlation [9] is 1270 Btu/hr-ft$^2$-°F. This value of h was further ascertained from the natural convection portion of the q-$\Delta T$ curve Figure 3. We actually had data points, not all shown in Figure 3, for the full range of the natural convection curve. They obeyed a $\Delta T^{5/4}$ relationship and gave h = 1400 Btu/hr-ft$^2$-°F at the inception of boiling. An h in this range gives $P \simeq 3.1$ for the case under consideration.

From Figure 7 we find that for $Pe \simeq 3.1$, $\Theta_o \simeq 1.1$. This

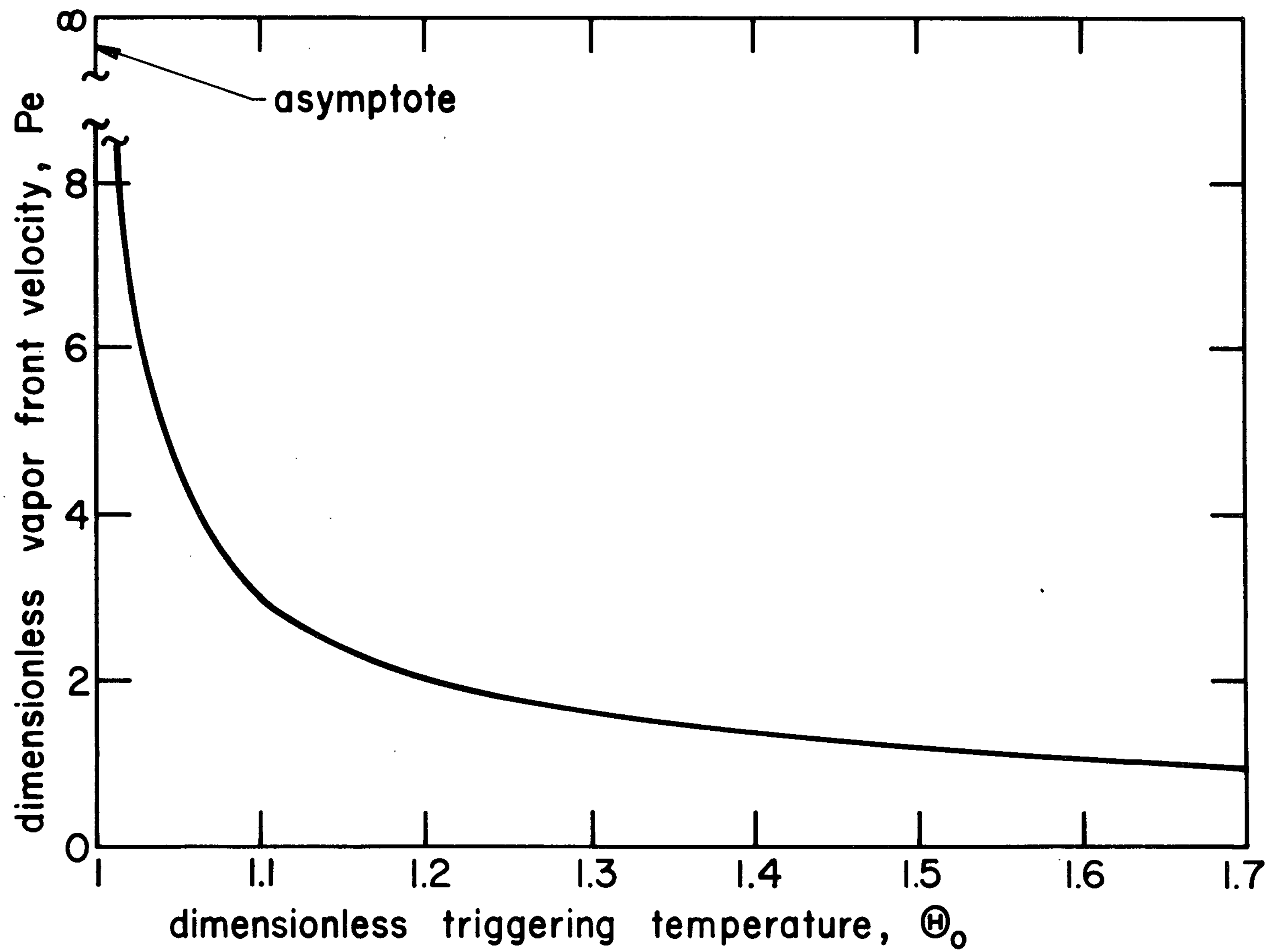


Fig. 7 Influence of triggering temperature on vapor front velocity

means that nucleation is triggered spontaneously along the wire when $(T-T_\infty)$ exceeds, by about 10%, the $(T_e-T_\infty)$ for the highest non-boiling heat flux.

## IV SUMMARY

A. At small values of R', the inertially-dominated hydrodynamic mechanism of transition in the pool boiling heat flux cease to occur on cylinders.

B. These mechanisms are replaced with a boiling process in which q rises monotonically in the wall superheat. The peak and minimum heat fluxes cease to occur somewhere in the range $0.02 < R' < 0.07$. Further work will be required to locate this point precisely.

C. The mechanism at small R' is as follows. As q is increased from a small value, heat is removed by natural convection. Natural convection is quite effective and nucleation is hard to trigger on the small wire we employed.[1] Hence this process continues to a relatively high heat flux.

The first nucleation blankets the wire since there is insufficient buoyancy to remove vapor until the bubble grows large with respect to the wire.[2] The vapor region then propagates axially until the vapor buoys away and allows some

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[1]This situation might be different for larger cylinders at low gravity.

[2]This situation would be the same for larger cylinders at low gravity.

internal cooling. The prevalence of randomly appearing and disappearing patches increases with increasing q until the wire is fully blanketed.

D. The speed of propagation of a vapor patch is established by the fact that the vapor interface will move into any region of the wire that has reached a critical triggering temperature for nucleation. In dimensionless coordinates, the relation between the triggering temperature and the propagation speed is given by the implicit relation, equation (18).

## LITERATURE CITED


1. Sun, K.H. and Lienhard, J.H., "The Peak Pool Boiling Heat Flux on Horizontal Cylinders", Bulletin 88, May 1969, College of Engineering, University of Kentucky.

2. Pitts, C.C. and Leppert, G., "The Critical Heat Flux for Electrically Heated Wires in Saturated Pool Boiling," Int. J. Heat Mass Transfer, vol. 9, 1966, pp. 365-377.

3. Siegel, R. and Keshock, E.G., "Effects of Reduced Gravity on Nucleate Boiling Bubble Dynamics in Saturated Water", A.I.Ch.E. Journal, vol. 10, No. 4, July 1964, pp 509-516.

4. Lienhard, J.H. and Watanabe, K., "On Correlating the Peak and Minimum Boiling Heat Fluxes with Pressure and Heater Configuration," Jour. Heat Transfer, vol. 88, 1966, p. 94.

5. Siegel, R. and Howell, J.R., "Critical Heat Flux for Saturated Pool Boiling from Horizontal and Vertical Wires in Reduced Gravity," NASA Tech. Note TND-3123, Dec. 1965.

6. Nukiyama, S., "The Maximum and Minimum Values of the Heat Q Transmitted from Metal to Boiling Water under Atmospheric Pressure," Trans. JSME, vol. 37, 1934, p. 367. (Reprinted in Int. Jour. Heat Mass Transfer, vol. 2, 1966, pp. 1419-1433).

7. VanStralen, S.J.D. and Sluyter, W.M., "Investigation on the Critical Heat Flux of Pure Liquids and Mixtures under Various Conditions," Int. J. Heat Mass Transfer, vol. 12, 1969, pp. 1353-1384.

8. Carslaw, H.S., and Jaeger, J.C., Conduction of Heat in Solids, Oxford, 1967, pp. 339.

9. McAdams, W.H., Heat Transmission, Third Ed., McGraw-Hill, 1954, pp 176.

## NOMENCLATURE

| | |
|---|---|
| $A$ | cross-sectional area of cylindrical wire, or arbitrary constant |
| $Bi$ | Biot number, $hA/kP$ |
| $C$ | constant, $\ln C = .57722$ |
| $G$ | volumetric heat generation rate in the wire, $2q/R$ |
| $q$ | acceleration of a system in a force field |
| $h$ | heat transfer coefficient, $q/\theta_e$ |
| $k$ | thermal conductivity |
| $L$ | characteristic length |
| $L'$ | dimensionless characteristic length |
| $N$ | fin constant, $\sqrt{hP/kA}$ |
| $P$ | perimeter of a cylindrical wire |
| $Pe$ | dimensionless group defined by equation (8) |
| $q, q_{max}, q_{min}$ | heat flux; subscripts max and min denote the peak and minimum boiling heat fluxes, respectively |
| $q_{max_F}, q_{min_F}$ | Zuber's predicted peak and minimum heat fluxes for a flat plate |
| $R$ | radius of a cylindrical wire |
| $R'$ | dimensionless radius, $R\,[g(\rho_f - \rho_g)/\sigma]^{1/2}$ |
| $r$ | radial distance in cylindrical co-ordinates |
| $T, T_{sat}$ | Temperature; subscript sat denotes saturation temperature |
| $t$ | time |
| $u$ | speed of vapor patch propagation |

| | |
|---|---|
| $x, x_b$ | axial distance coordinate; subscript b denotes reversed coordinate under the blanketed portion of the wire |

Greek Letters

| | |
|---|---|
| $\alpha$ | thermal conductivity |
| $\mu_f$ | liquid viscosity |
| $\rho_f$ | saturated liquid density |
| $\rho_g$ | saturated vapor density |
| $\sigma$ | surface tension between a saturated liquid and its vapor |
| $\theta$ | temperature measured above the ambient saturation temperature |
| $\theta_e$ | equilibrium temperature, q/h |
| $\theta_o$ | vapor patch triggering temperature (equal to the Leidenfrost temperature under the arguments developed in this report) |
| $\Theta$, $\Theta_o$ | dimensionless temperature, $\theta/\theta_e$ and $\theta_o/\theta_e$ |
| $\xi$ | dimensionless axial parameter, xN |

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